

# Flare Systems Exploitation and Impact on Permafrost

**M Yu Filimonov<sup>1,2</sup> and N A Vaganova<sup>1,2</sup>**

<sup>1</sup> Ural Federal University, Yekaterinburg, Russia

<sup>2</sup> IMM UB RAS, Yekaterinburg, Russia

fmy@imm.uran.ru

**Abstract.** Mathematical models and numerical algorithms of horizontal and vertical flare systems exploitation in northern oil and gas fields located in permafrost zone are developed. Computations of long-term forecasts of permafrost degradation around such constructions have been carried out for various types of operation, including emergency situations, which cause a short-term increase in the heat flow near the ground surface, which leads to an additional soil temperature increasing.

## 1. Introduction

Permafrost occupies about 25% of the land area [1]. These territories occupy approximately 80%, 60% and 50% of the total area in Alaska, in Russia, and in Canada, respectively. In the permafrost zone of Russia, about 93% of Russian natural gas and 75% of oil are produced. An estimation of the reserves in the Arctic part of Russia consist of 7.6 billion tons of oil and 66.9 trillion cubic meters of gas.

When different technical systems are placed on a cluster sites used in the northern oil and gas fields, it is necessary to minimize the influence of various heat sources to the frozen ground. This is caused that thawing of permafrost can be accompanied by subsidence of the earth's surface and appearance of dangerous permafrost geological processes, called thermokarst, which leads to serious disasters. The problem of reducing the intensity of thermal interaction in the system “engineering facility (heat source) – soil” is of particular importance for solving energy conservation, environmental protection, safety, saving costs and improving the operational reliability of various technical systems. In this paper, the main attention is paid to investigation of the effect of vertical flare systems (VFS) and horizontal flare systems (HFS) on permafrost degradation and long-term forecast of the thawing zone dynamics under the flare systems.

## 2. The problem statement

Simulation of the processes of heat propagation in a permafrost soil reduces to solving a three-dimensional equation of contact (diffusion) heat conductivity with inhomogeneous coefficients in a domain, including the localized heat of the phase transition – an approach that allows to solve a Stefan-type problem without pre-determination of boundary of phase transition. Let consider a three-dimensional area large enough to avoid artificial influence of lateral and bottom boundaries. The equation for the temperature  $T=T(t,x,y,z)$  in the soil has the form

$$\rho \left( c_v(T) + k\delta(T - T^*) \right) \frac{\partial T}{\partial t} = \operatorname{div} \left( \lambda(T) \operatorname{grad} T \right), \quad (1)$$



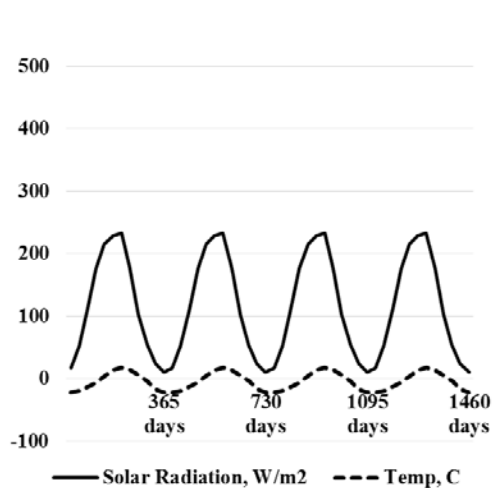


Fig. 1. The cyclic changes in solar radiation  $q(t)$  (solid line) and air temperature  $T_{air}$  (dashed line) during 4 years.

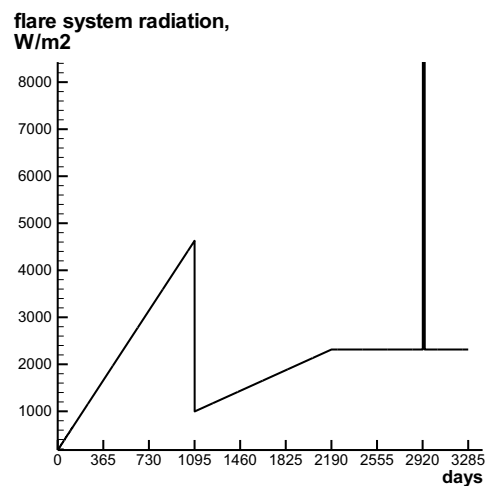


Fig. 2. The heat flux  $f(x,y)$  from a vertical flare system.

where  $\rho=\rho(x,y,z)$  is density [kg/m<sup>3</sup>],  $T^*=T^*(x,y,z)$  is temperature of phase transition,  $c_v(T)=\begin{cases} c_1(x,y,z), & \text{for } T < T^*, \\ c_2(x,y,z), & \text{for } T > T^* \end{cases}$  is specific heat [J/kg K],  $\lambda(T)=\begin{cases} \lambda_1(x,y,z), & \text{for } T < T^*, \\ \lambda_2(x,y,z), & \text{for } T > T^* \end{cases}$  is thermal conductivity [W/m K],  $k=k(x,y,z)$  is specific heat of phase transition,  $\delta$  is Dirac  $\delta$ -function.

The coefficients included in equation (1) may vary at different points in the computational domain because of heterogeneity of the soil and possible presence of engineering structures. The ground surface is the main zone of formation of the natural thermal fields. On this surface the equation of balance of flows is used as a boundary condition, with taking into account the main climate factors: air

concrete slab 0.3 m	riprap to 5.7 m.
broken stone 4 m	
foam concrete 0.6 m	
penoplex 0.3 m	
sand 0.5 m	
permafrost -0.3°C to 50 m	

Fig. 3. A rriprap for a vertical flare system

concrete slab 0.15 m	riprap to 2.45 m.
broken stone 0.2 m	
sand 2.1 m	
permafrost -2.4°C to 50 m	

Fig. 4. A rriprap for a horizontal flare system

temperature and solar radiation. In Fig. 1 the cyclic changes in solar radiation  $q$  and air temperature  $T_{air}$  during 4 years are shown.

We will consider two types of flare systems: horizontal flare system (HFS), when the flame is in contact with the ground, and vertical flare system (VFS), when the flame of burning gas does not

touch the ground, but effect on it by thermal radiation. For the position of HFS it is necessary to set a fixed temperature equal to the flame temperature. The zone of influence of the VFS flare may be approximated as a circle with radius  $R_f$ . As a boundary condition on the surface of the ground, the following equation of the balance of heat flows is used, which also takes the radiation from the flare:

$$f(x, y, t) + \alpha q + b(T_{air} - T|_{z=0}) = \varepsilon \sigma (T^4 - T_{air}^4) + \lambda \frac{\partial T}{\partial z} \Big|_{z=0}, \quad (2)$$

where  $f(x, y, t)$  is a density of heat flow from the flame. It may be determined as

$$f(x, y) = \begin{cases} 0, & \text{if } (x - x_f)^2 + (y - y_f)^2 > R_f^2, \\ \left(1 - \frac{\sqrt{(x - x_f)^2 + (y - y_f)^2}}{R_f}\right)^2 P_f, & \text{if } (x - x_f)^2 + (y - y_f)^2 \leq R_f^2. \end{cases}$$

The heat fluxes (for example, Fig. 2) from the flares has an extremely influence on the soil in compare with the natural heat sources: sun and air (Fig. 1). For example, in Fig. 2, the scenario of the operation of a vertical flare system is presented, taking into account an emergency discharge of gas in a short time interval.

**Table 1.** Thermal parameters of the riprap layers and the soil.

	Thermal conductivity, frozen W/(m K)	Thermal conductivity, melted, W/(m K)	Volumetric heat, frozen, kJ/(m <sup>3</sup> K)	Volumetric heat, melted, kJ/(m <sup>3</sup> K)	Heat of phase transition, kJ/(m <sup>3</sup> K)
<b>concrete slab</b>	1.93	1.57	2150.0	3490.0	141504.0
<b>broken stone</b>	1.75	1.63	2160.0	2630.0	83616.0
<b>sand</b>	1.83	1.39	1536.0	1983.0	69505.8
<b>permafrost soil</b>	1.89-2.22	1.68-1.75	2200.0-2350.0	2750.0-2780.0	90983.7-10120.0

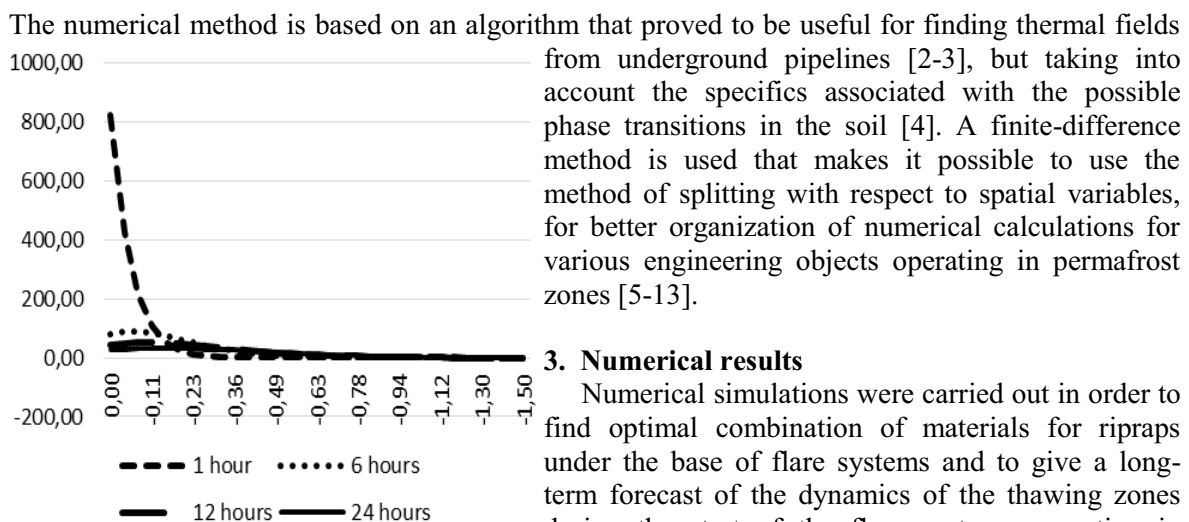


Fig. 5. Temperature in soil under HFS: heating during 1 hour and cooling in the following.

### 3. Numerical results

Numerical simulations were carried out in order to find optimal combination of materials for ripraps under the base of flare systems and to give a long-term forecast of the dynamics of the thawing zones during the start of the flare systems operation in March. A number of variants of such ripraps were considered, for example, in Fig. 3 and Fig. 4.

In the following, we will consider a permafrost soil with parameters presented in Table. 1.

To simulate the operation of the HFS, the temperature distribution from the flare on the surface of the ground is set in a rectangle area. The hottest area is  $820^{\circ}\text{C}$  in the center, then the temperature

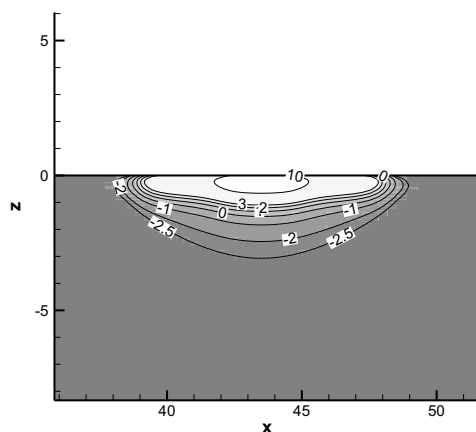


Fig. 6. Temperature field under HFS on March for 8 years of exploitation.

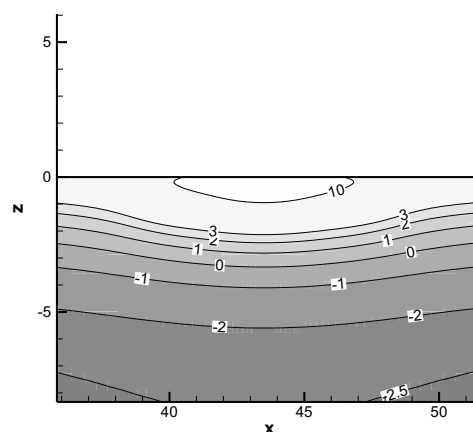


Fig. 7. Temperature field under HFS on September for 8 years of exploitation.

decreases to the boundary of the flare platform to the background temperature. We assume that the system operates in the following periodic mode: the gas flaring is carried out during 1 hour every 7 days. Respectively, the temperature increases to  $820^{\circ}\text{C}$  only in this short period and then the soil is under influence of natural thermal fields and is cooling. In Fig. 5 the temperature profiles under the center of HFS are shown for the cooling period.

This mode of operation leads to the computations have to be performed with variable time steps for the long-term forecasting of thawing zones. In Fig. 6 and Fig. 7 the thermal fields near the surface are shown on March and September, respectively, after simulation of 30 years of exploitation.

Now, let consider a vertical flare system operation by scenario, presented in Fig. 2. As a result of numerical simulations of thermal fields forming as a result of VFS operation, it was found, that on the “ground-air” surface in the zone of influence of VFS there still are under significant seasonal

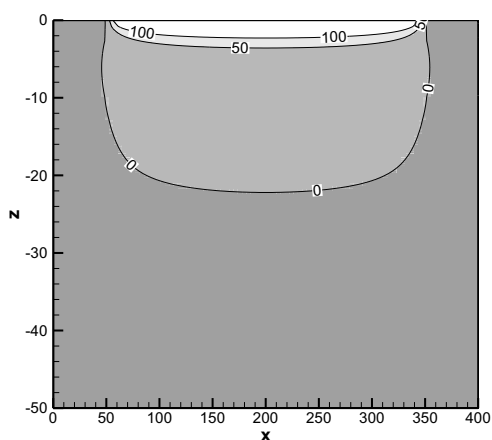


Fig. 8. Thawing lines in the soil without a riprap under HFS after 30 years of exploitation in March.

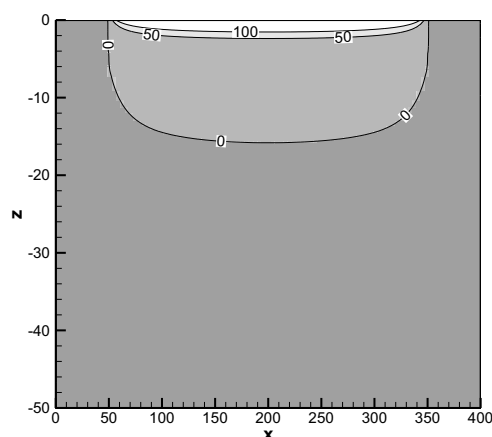


Fig. 9. Thawing lines in the soil with 5.7 m. riprap under HFS after 30 years of exploitation in March.

temperature fluctuations. The temperature on the surface of the zone of influence of the flame increases; the growth of the thawing zone stabilizes at 22-23 meters and 16-17 meters for the soil without a riprap (Fig. 8) and with a riprap (Fig. 9), respectively. Comparison of scenarios with an emergency flaring and an ordinary mode shows that the surface heating increases by 50°C and the effect of this is no more than 1°C after six months. The melted zone formation is a result more by the total power of the VFS supported for a long time. A short-term increase in the power of the VFS will only heat up near-surface layers of the soil. It is preferable to carry out emergency discharges for VFS during the cold season, in order to compensate for the additional heat.

#### 4. Conclusion

The developed models and programs allow to carry out calculation of long-term effect on permafrost thawing from horizontal and vertical flare systems, taking into account various scenarios for emergency gas discharge. It is possible to make computations for a long time interval with variable time steps and, if necessary, to simulate any technological processes that take place in a limited period of time. The estimations of the temperature profiles in the ground can serve as a guide for constructing an optimal riprap under flare systems, and allow to determine the temperature in different layers of ground and to take into account heat resistance of insulations materials for stabilization of the thawing zones in permafrost.

#### Acknowledgments

This work was supported by RFBR projects (16-01-00401).

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